Recent Transverse Spin Results in Polarized p+p Collisions at PHENIX

Han Liu
Los Alamos National Lab

Outline

- Introduction
- The PHENIX Experiment
- Single Spin Asymmetry Measurements

  -- Mid-rapidity π^0 and charged hadrons

  -- Forward π^0 (MPC, Run6)

  -- Forward J/Ψ

  -- Forward neutron
- Summary and Outlook

A Brief History…

-- Kane, Pumplin, Repko '78

At leading twist and with collinear factorization, pQCD predicts small analyzing powers in transversely polarized p+p collisions

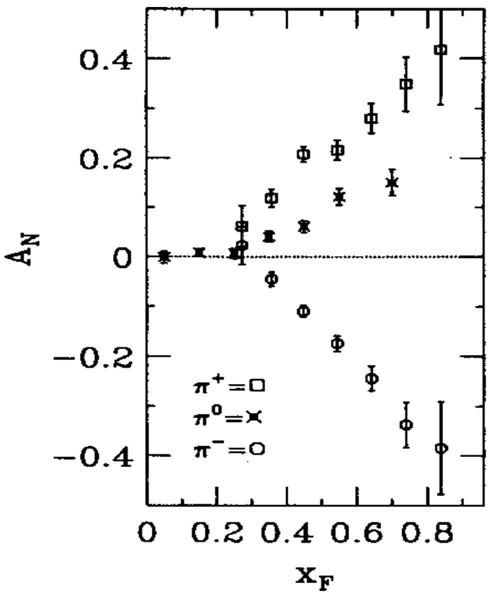
$$A_N \propto \frac{m_q}{\sqrt{s}} \text{ (for example, } \mathrm{m_q} = 3MeV, \sqrt{s} = 20GeV, A_N \approx 10^{-4})$$

-- FermiLab E704 experiment

Found strikingly large transverse single-spin effects in p↑+p fixed-target collisions with 200 GeV polarized proton beam

$$p_{\uparrow} + p \rightarrow \pi + X$$

√s= 20 GeV, p_T=0.5-2.0 GeV/c



π^0 : PLB261 (1991) 201

$\pi^{+/-}$: PLB264 (1991) 462

Theoretical efforts

Four different mechanisms have been propose to explain this asymmetries

- Sivers effect

-- Transverse momentum dependent quark and gluon distributions give rise to correlation between transverse proton spin and the transverse momentum k_T of quarks and gluons

- Collins effect

-- Transversity distributions + spin dependent fragmentation functions

- Higher-twist effects

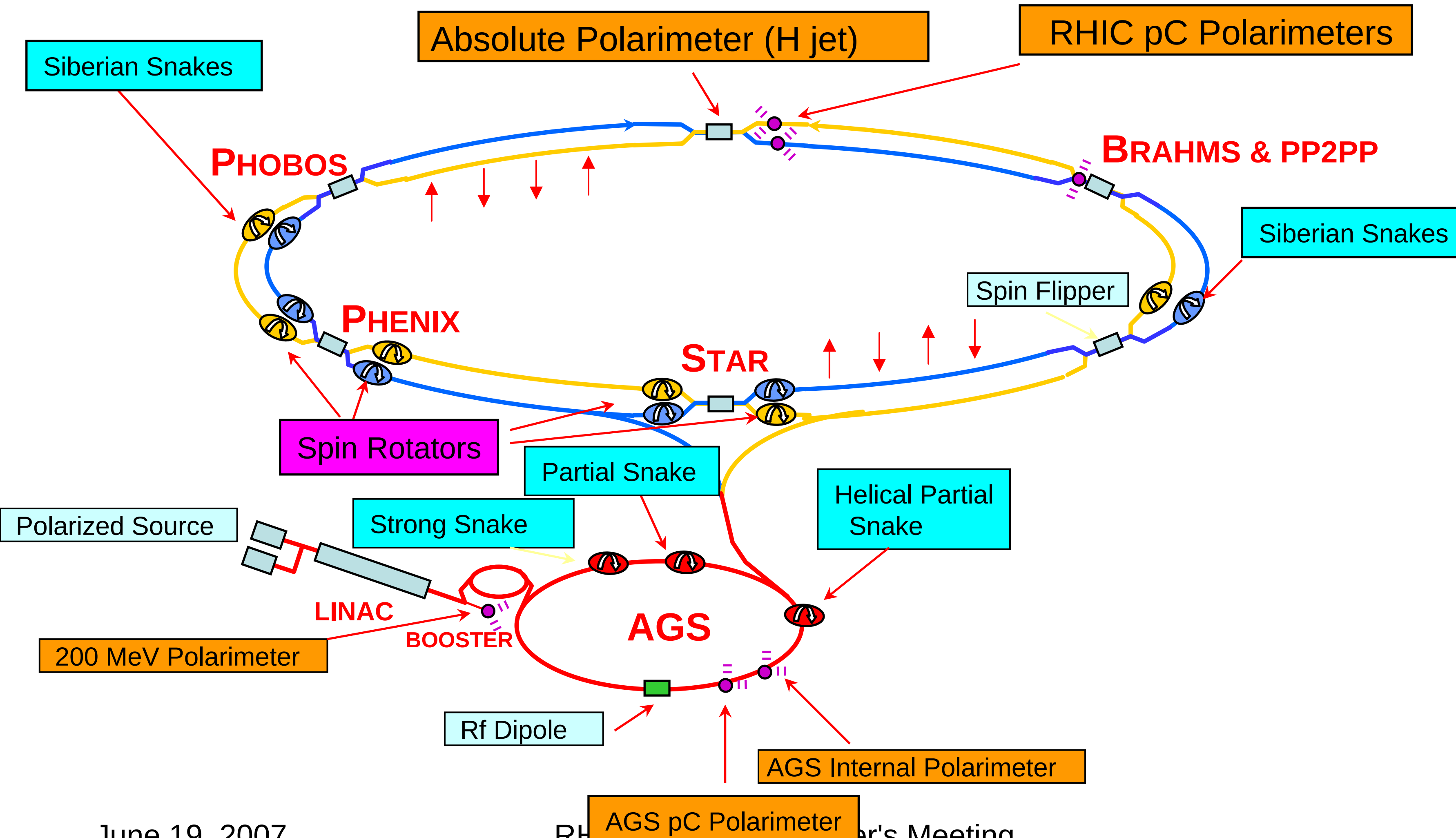
-- Quark gluon field interference

* Sterman and Qiu → Initial State Twist 3
* Koike → Final State Twist 3

A coherent treatment of the Sivers effect and quark gluon correlations at higher twist has been provided by Ji, Qiu, Vogelsang and Yuan (**PRL97**:082002,2006)

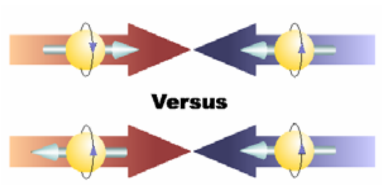
- Or some combination of above

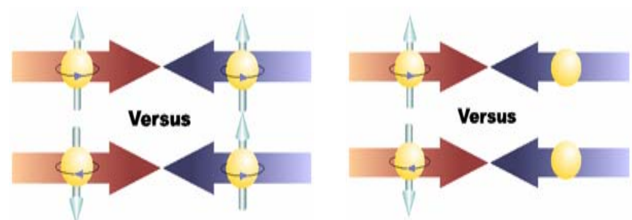
RHIC as a Polarized p+p Collider

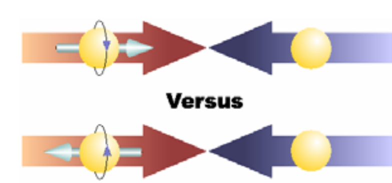


Proton Spin Structure at PHENIX

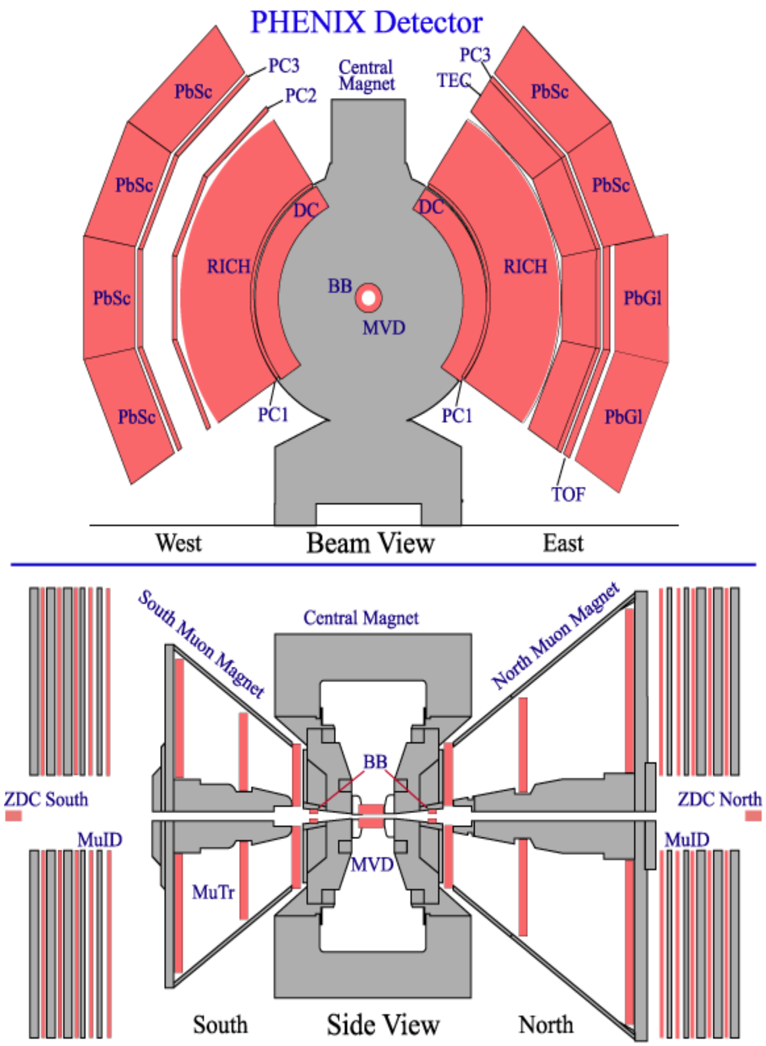
First moment of the spin dependent gluon disbribution ΔG	Transverse Spin	Flavor separation of the quark and anti-quark sea Δq and $\Delta \bar{q}$
Inclusive Hadron Production $A_{LL}(gg,gq \rightarrow h+X)$ Prompt Photon $A_{LL}(gq \rightarrow \gamma + X)$ Heavy Flavors $A_{LL}(gg \rightarrow c\bar{c}, b\bar{b} + X)$	Single Spin Asymmetries A_N Transversity δq: π^+, π^- Interference fragmentation: $A_T\left(p_\perp p \rightarrow (\pi^+, \pi^-) + X\right)$ Drell Yan A_{TT}	W Production $A_L(u + \bar{d} \rightarrow W^+ \rightarrow \ell^+ + \nu_l)$ $A_L(\bar{u} + d \rightarrow W^- \rightarrow \ell^- + \bar{\nu}_l)$







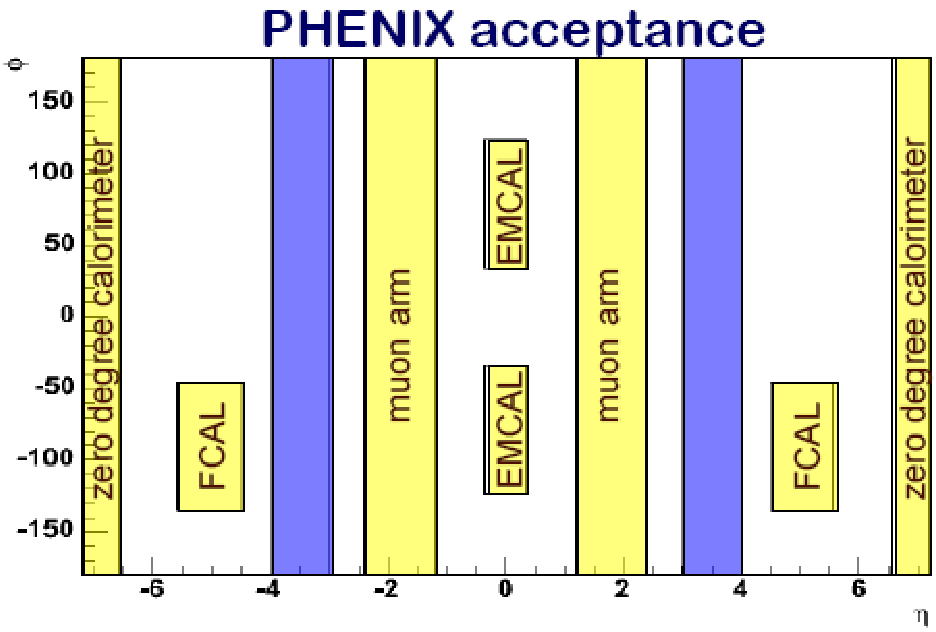
The PHENIX Detectors for Spin Physics



- **Central Arm Tracking** **$|\eta| < 0.35$, $x_F \sim 0$**
  - Drift Chamber (DC)
    - momentum measurement
  - Pad Chambers (PC)
    - pattern recognition, 3d space point
  - Time Expansion Chamber (TEC)
    - additional resolution at high pt
- **Central Arm Calorimetry**
  - PbGl and PbSc
    - Very Fine Granularity
      - Tower $\Delta\phi x \Delta\eta \sim 0.01x0.01$
    - Trigger
- **Central Arm Particle Id**
  - RICH
    - electron/hadron separation
  - TOF
    - π/K/p identification
- **Global Detectors (Luminosity,Trigger)**
  - BBC **$3.0 < |\eta| < 3.9$**
    - Quartz Cherenkov Radiators
  - ZDC/SMD (**Local Polarimeter)**
    - Forward Hadron Calorimeter
- **Forward Calorimetry** **$3.1 < |\eta| < 3.7$**
  - MPC
    - $PbWO_4$ Crystal
- **Forward Muon Arms**

  South arm: $-2.0 < \eta < -1.2$
  North arm: $1.2 < \eta < 2.4$

Recent PHENIX A_N Measurements



- Mid-rapidity π^0/ $h^\pm$
- Forward π^0 with Muon Piston Calorimeter
- Forward rapidity J/ Ψ
- Forward neutron

PHENIX polarized-proton runs

Longitudinally Polarized Runs

Year	$\sqrt{s}$ [GeV]	Recorded L	Pol [%]	FOM (P^4L)
2003 (Run 3)	200	.35 pb^{-1}	27	1.5 nb^{-1}
2004 (Run 4)	200	.12 pb^{-1}	40	3.3 nb^{-1}
2005 (Run 5)	200	3.4 pb^{-1}	46	150 nb^{-1}
2006 (Run 6)	200	7.5 pb^{-1}	62	1100 nb^{-1}
2006 (Run 6)	62.4	.08 pb^{-1}	48	4.2 nb^{-1}

Transversely Polarized Runs

Year	$\sqrt{s}$ [GeV]	Recorded L	Pol [%]	FOM (P^2L)
2001 (Run 2)	200	.15 pb^{-1}	15	3.4 nb^{-1}
2005 (Run 5)	200	.16 pb^{-1}	47	38 nb^{-1}
2006 (Run 6)	200	2.7 pb^{-1}	57	880 nb^{-1}
2006 (Run 6)	62.4	.02 pb^{-1}	48	4.6 nb^{-1}

Asymmetry calculation

- Square root formula

$$A_N = \frac{1}{P} \cdot \frac{\sqrt{N_L^{\uparrow} \cdot N_R^{\downarrow}} - \sqrt{N_R^{\uparrow} \cdot N_L^{\downarrow}}}{\sqrt{N_L^{\uparrow} \cdot N_R^{\downarrow}} + \sqrt{N_R^{\uparrow} \cdot N_L^{\downarrow}}}$$

P – Beam polarization (CNI)

R – Relative luminosity (BBC, ZDC)

- Luminosity formula

$$A_N = \frac{1}{P} \cdot \frac{N^{\uparrow} - R \cdot N^{\downarrow}}{N^{\uparrow} + R \cdot N^{\downarrow}} \qquad R = \frac{L^{\uparrow}}{L^{\downarrow}}$$

$$A_N = \frac{A^{incl} - r \cdot A^{BG}}{1 - r}$$

$$\delta A_N = \frac{\sqrt{(\delta A^{incl})^2 + r^2 \cdot (\delta A^{BG})^2}}{1 - r}$$

$$r = \frac{N^{BG}}{N^{incl}}$$

π^0 and charged hadrons at Mid-rapidity

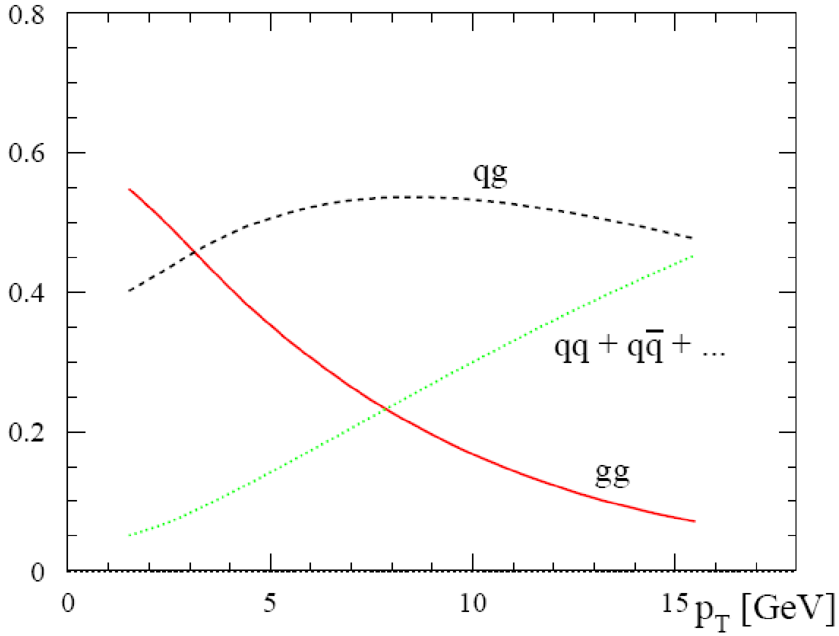
- Why Measure A_N of Different Particle Species at Mid-rapidity in PHENIX?

-- Different kinematic regions

-- Currently dominated by gg and gq scattering, mainly probes the Sivers effect

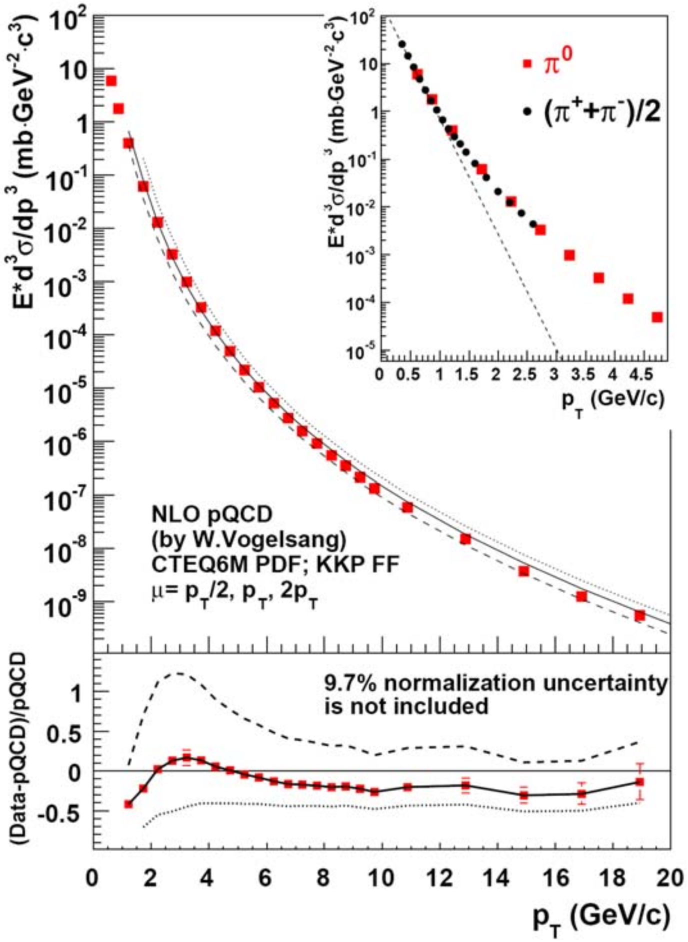
-- Future measurements will be dominated by quark scattering, more sensitive to transversity + Collins

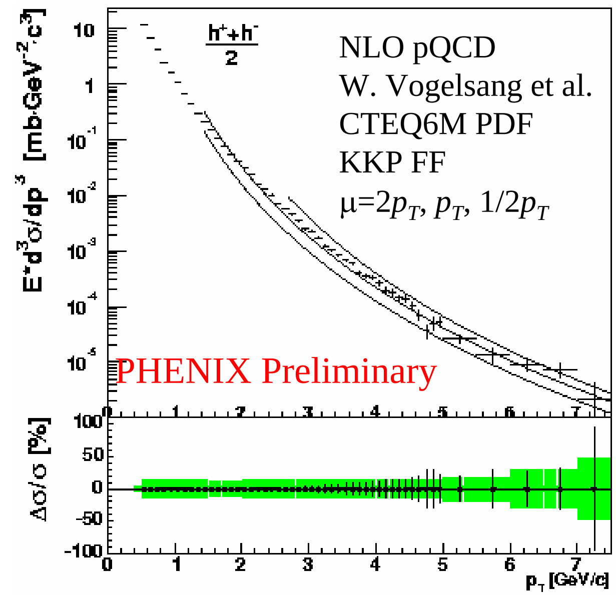
Fraction of pion production



Mid-Rapidity π^0 and charged hadron Cross Section Measurements at $\sqrt{s}$ = 200 GeV

arXiv:0704.3599 [hep-ex]





* NLO QCD Calculation Cross-sections consistent with Data

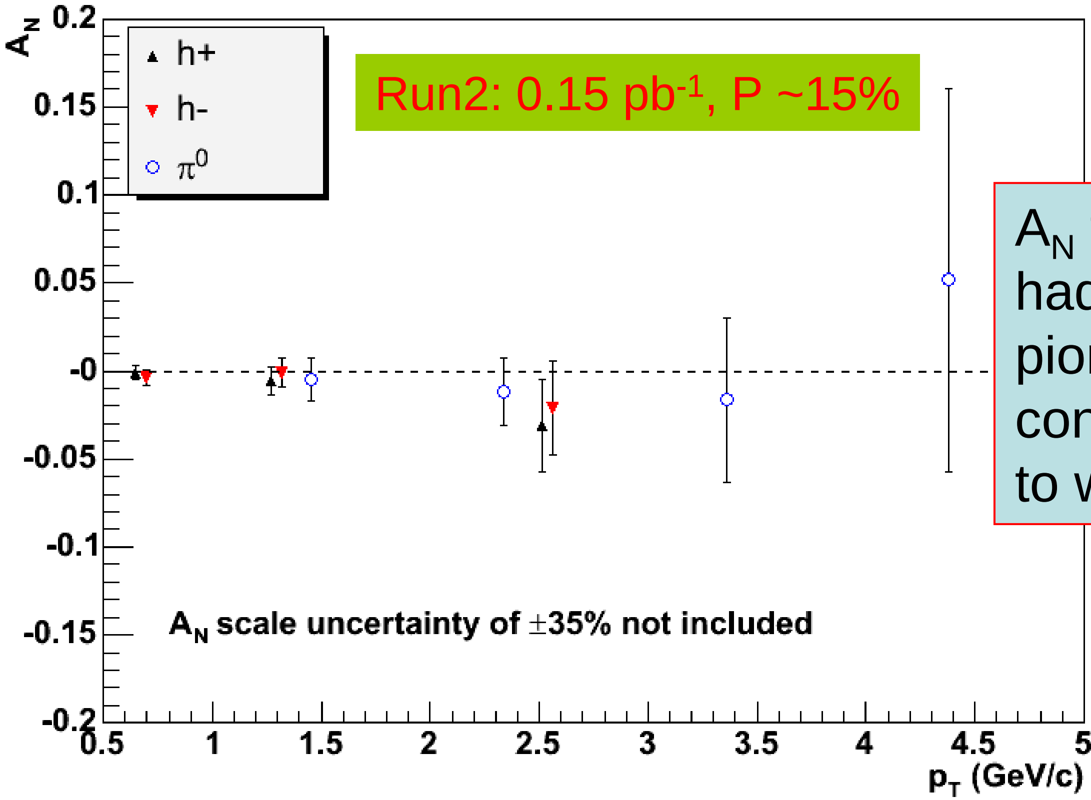
--- CTEQ6M pdf

--- KKP and Kretzer Fragmentation Fcns

* Necessary Confirmation that pQCD can be used successfully at RHIC to extract spin dependent pdf's

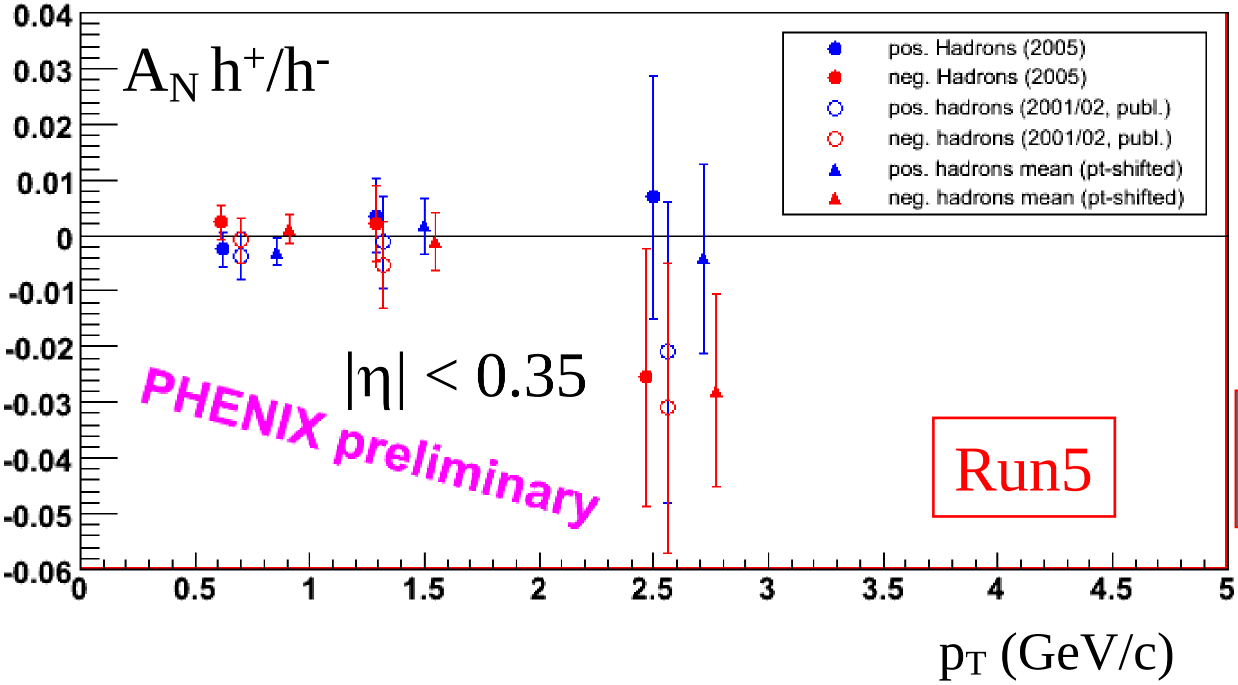
π^0 and charged hadrons A_N at Mid-rapidity

PRL 95(2005)202001



A_N for both charged hadrons and neutral pions at mid-rapidity consistent with zero to within a few percent

Update on charged hadrons A_N



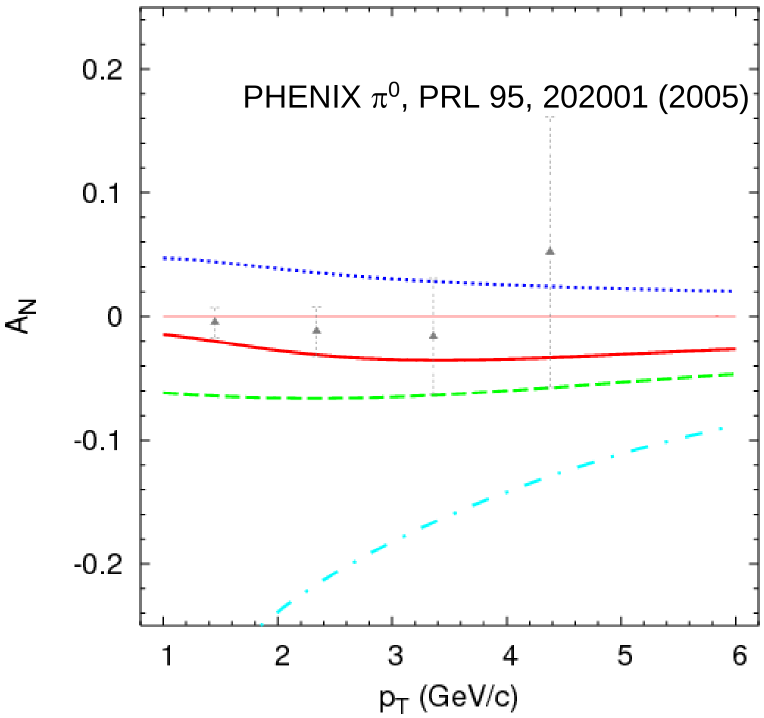
Improved polarization
P=15% in 2001/02
P=47% in 2005

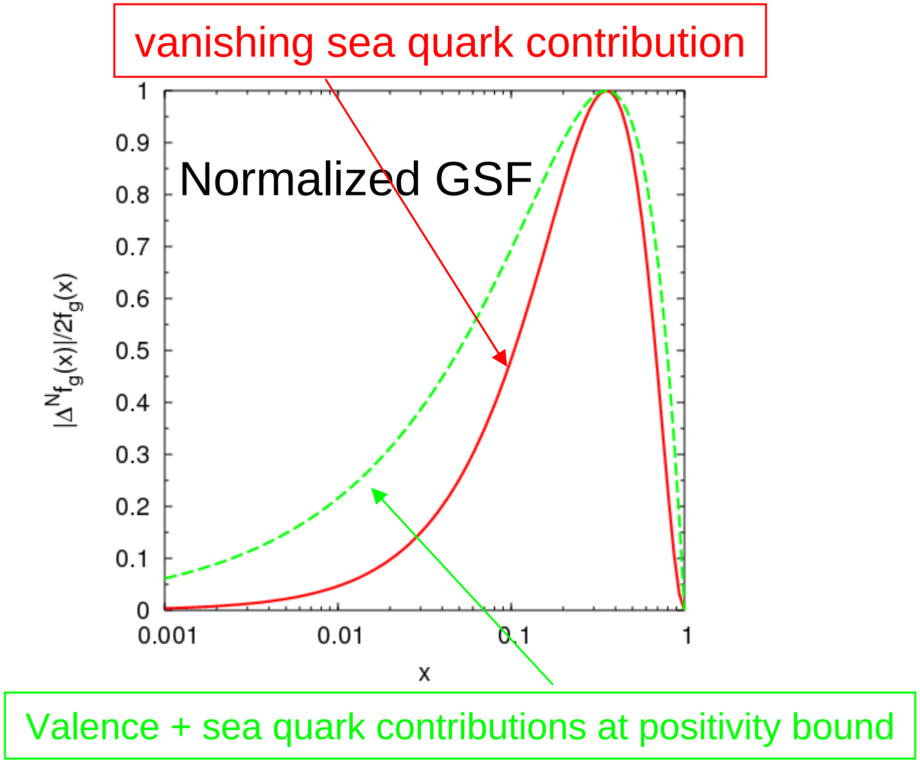
A_N is zero within 1% → contrast with forward pions

Can be used to provide upper limit on the gluon Sivers distribution
Anselmino et al, **PRD74**:094011,2006

Anselmino et al, **PRD74**:094011,2006

Constraints on Gluon Sivers?



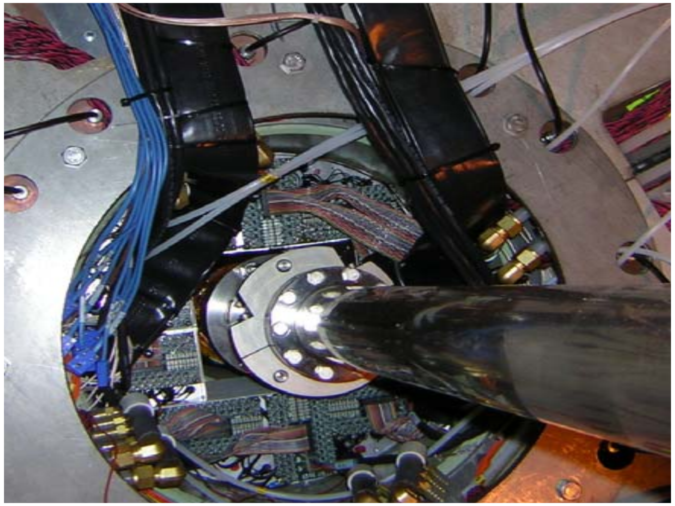


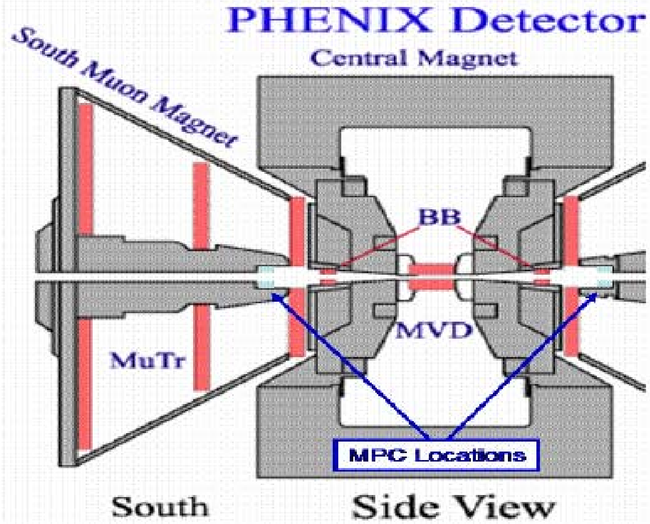
LO QCD Transverse Momentum Dependent parton scattering calculations

- Thin Red: valence u and d Sivers alone
- Cyan: Gluon Sivers Function at positivity bound, no sea quark Sivers
- Thick Red: Gluon Sivers parameterized to be 1 sigma from PHENIX π^0 A_N, no sea quark Sivers
- Blue: valence + sea quark Sivers at positivity bound
- Green: Gluon Sivers function and valence + sea quark at positivity bound → the largest gluons Sivers function compatible with our data

Forward π^0 at $\sqrt{s}$=62 GeV

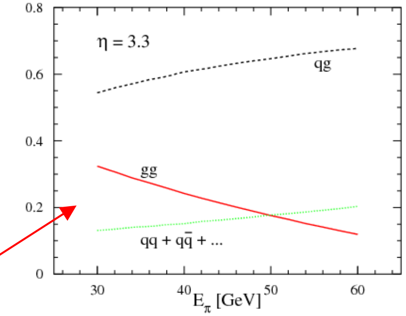
- New calorimeter (Muon Piston Calorimeter) added in Run6
- 192 2.2x2.2x18 cm^3 $PbWO_4$ crystals, 220 cm from vertex (behind Beam-Beam counter)
- $3.1 < |\eta| < 3.65$ (Region of large observed asymmetries)
- Only south arm in Run6
- Expect 200GeV longitudinal and 62.4GeV longitudinal & transverse results (very little useful 200GeV transverse data due to late electronics)



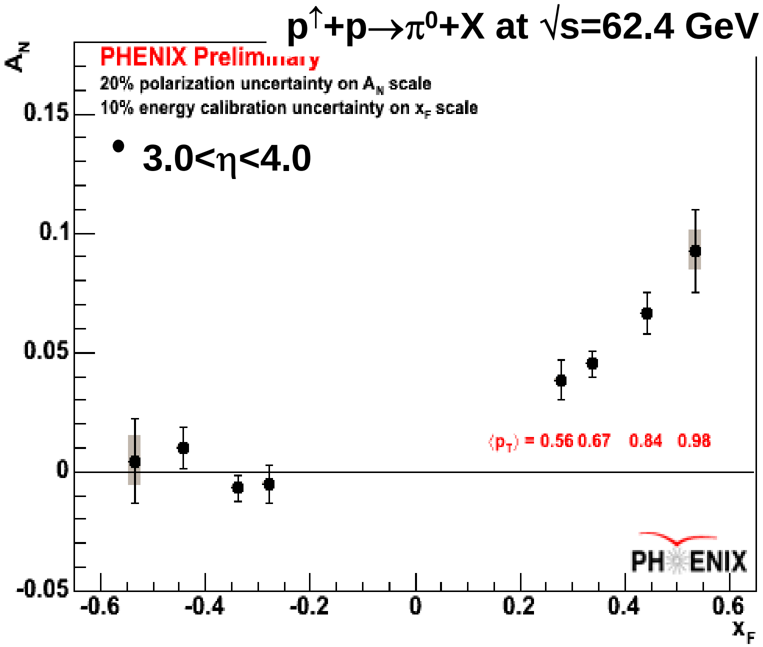


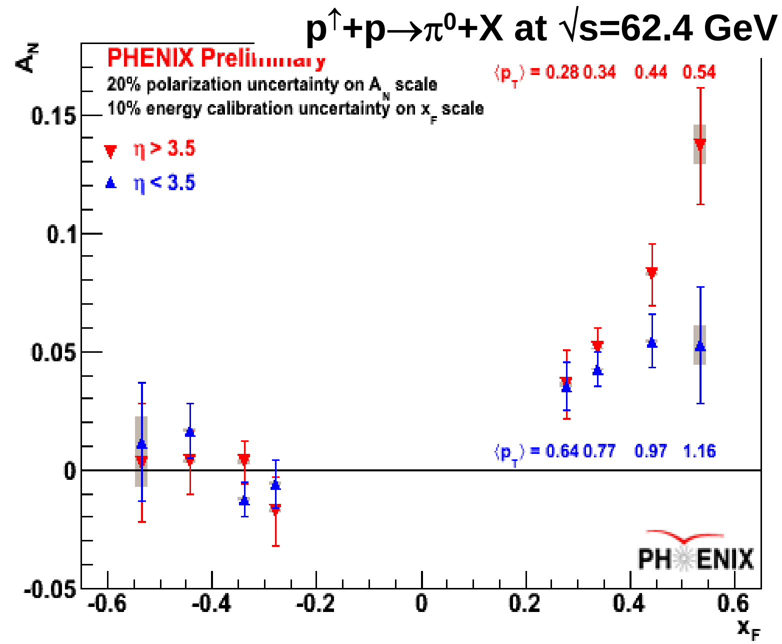
π^0 A_N at large x_F

PLB **603**,173 (2004)



process contribution to π^0, η=3.3, $\sqrt{s}$=200 GeV





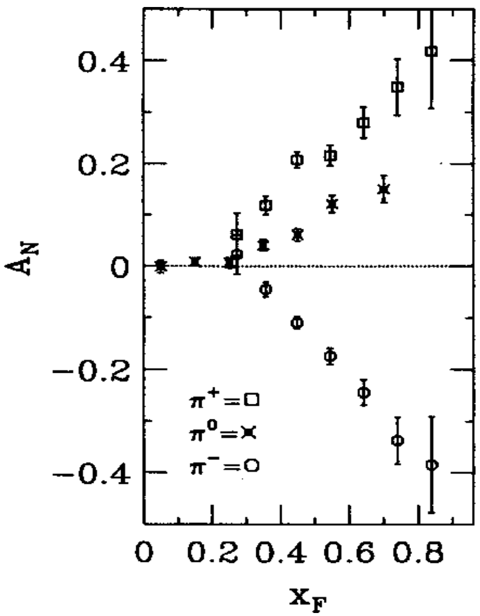
Asymmetry seen in yellow beam (positive x_F), but not in blue (negative x_F)

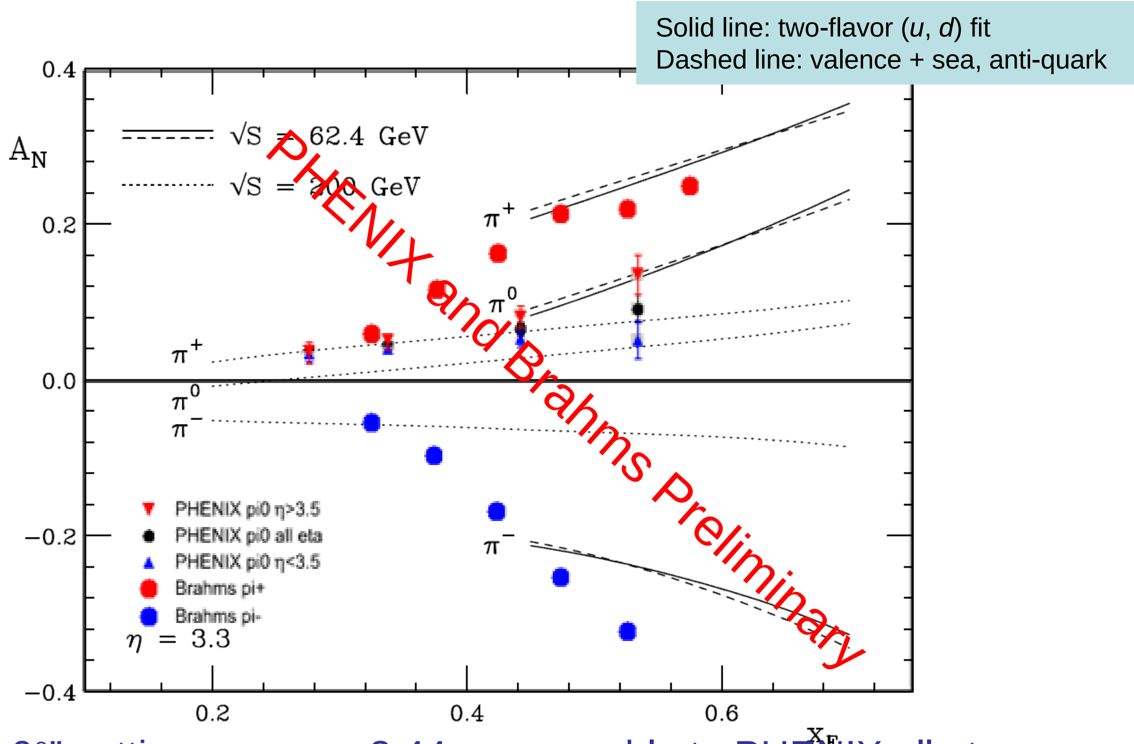
Large asymmetries at forward x_F → Valence quark effect?

x_F, p_T, $\sqrt{s}$, and η dependence provide quantitative tests for theories

RHIC Forward Pion A_N at 62.4 GeV

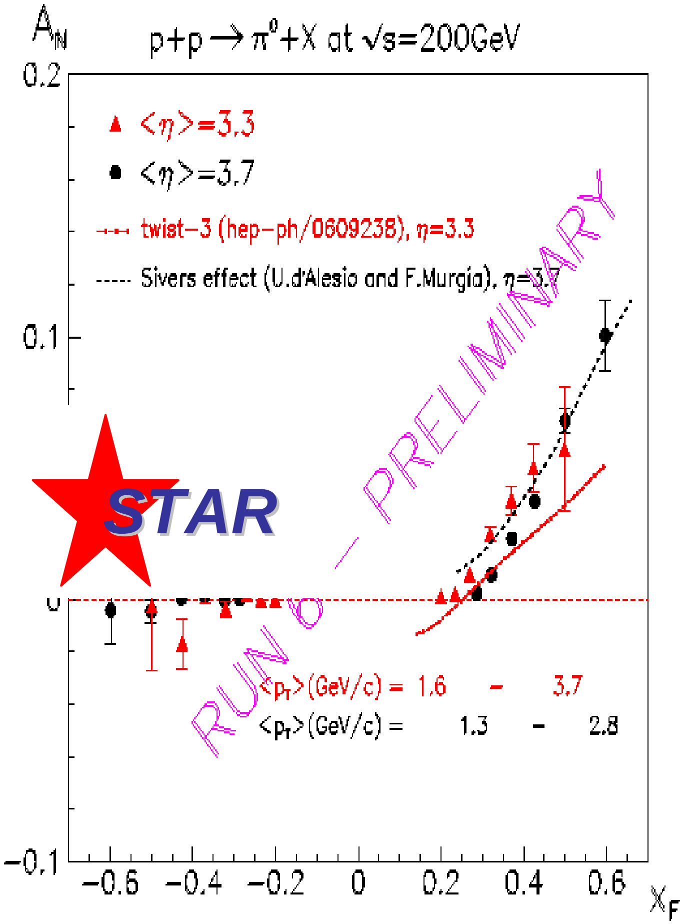
E704, 19.4 GeV, PLB 261, (1991) 201

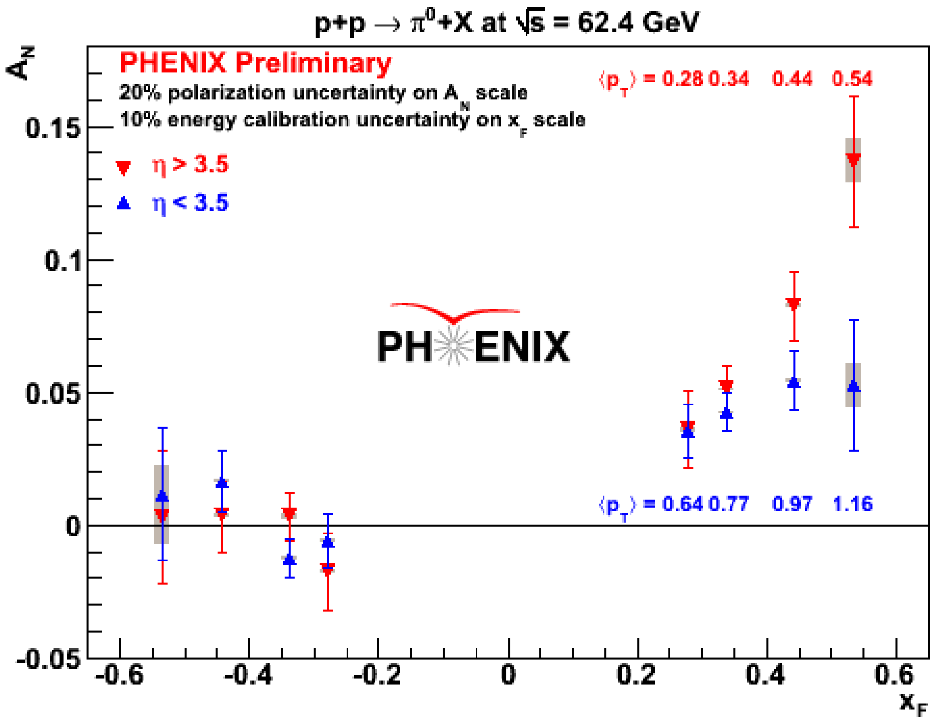




- Brahms Spectrometer at "2.3°" and "3.0°" setting → <η> = 3.44, comparable to PHENIX all eta
  - Qualitatively similar behavior to E704 data: pi0 is positive and between π^+ and π^-, and roughly similar magnitude: $A_N(\pi^+)/A_N(\pi^0)$ ~ 25-50%
  - Flavor dependence of identified pion asymmetries can help to distinguish between effects
- Kouvaris, Qiu, Vogelsang, Yuan, PRD74:114013, 2006
  - Twist-3 calculation for pions (η exactly at 3.3)
  - Derived from fits to E704 data at $\sqrt{s}$=19.4 GeV and then extrapolated to 62.4 and 200 GeV
  - Only qualitative agreement at the moment. Must be very careful in comparisons (between experiments and theories) that kinematics are matched, since A_N is a strong function of p_T and x_F

Comparison to π^0 at $\sqrt{s}$ = 200 GeV





-- The apparent opposite trend in theη dependence between STAR and PHENIX may result from the difference in collsion energy and p_T coverage

-- Theoretic calculations for $\sqrt{s}$ = 200 GeV appear to disagree with the experimental results

J/Ψ production at forward rapidity

Why J/ Ψ?

- Eliminate Collins' effects

  * J/Ψ production dominated by gluon gluon fusion at RHIC energy

  Pythia 6.1 simulation

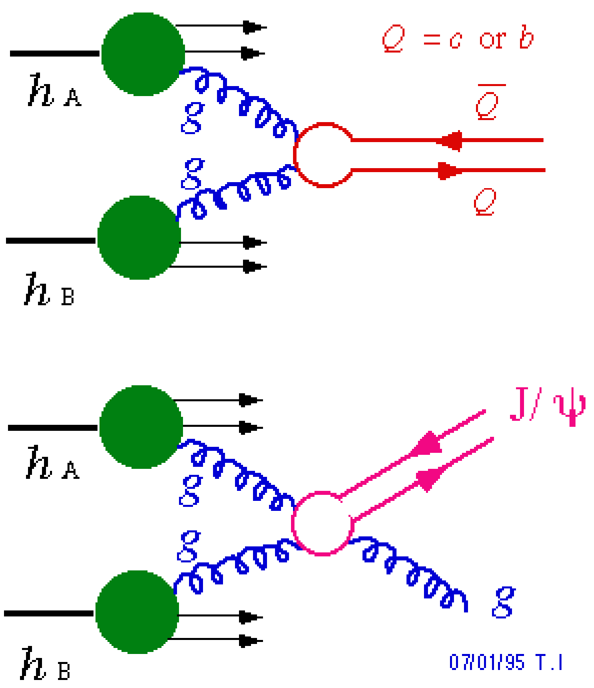
$c\bar{c}$:	$gg \rightarrow c\bar{c}$	95%
$b\bar{b}$:	$gg \rightarrow b\bar{b}$	85%

  * gluon has zero transversity

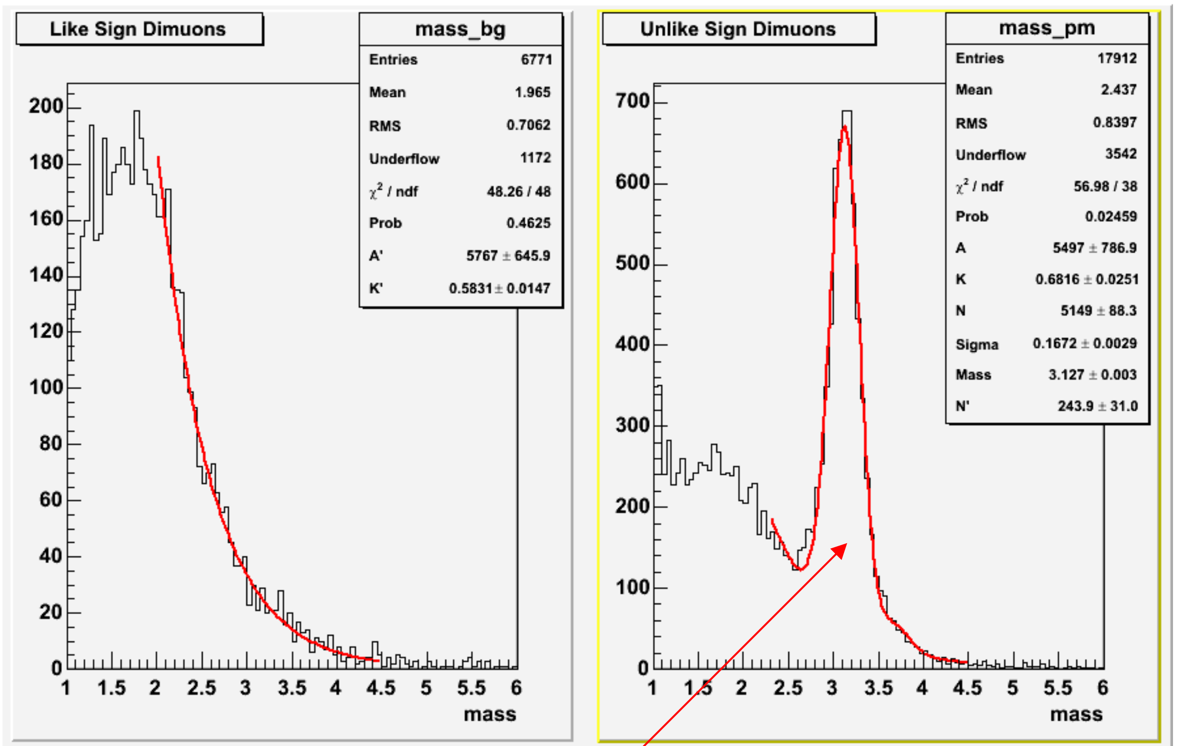
- A perfect channel for gluon Sivers function

- Important to understand the origin of observed large A_N at large x_F

Gluon Fusion



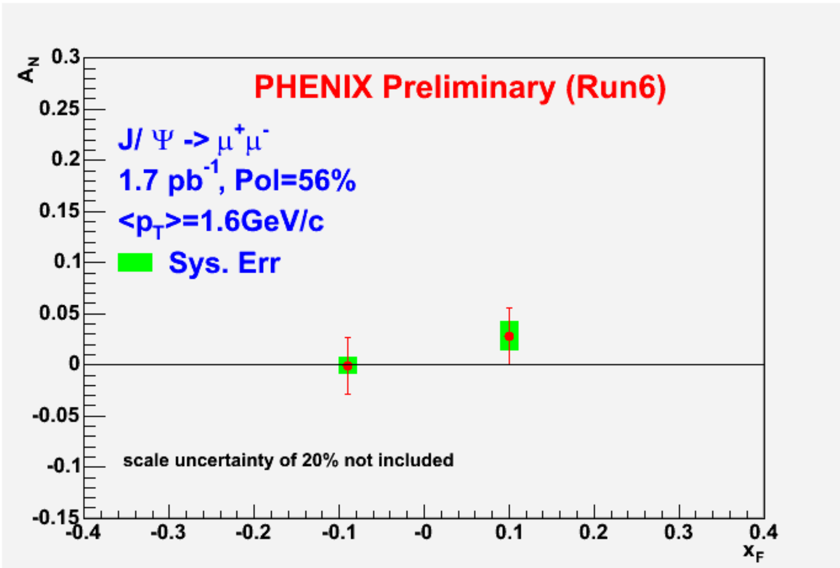
Like/Unlike charge signed dimuon mass spectra



Run6 Lvl2 data

$$\frac{dN}{dM} = A \cdot e^{-K \cdot M} + N \cdot \frac{1}{2\pi\sqrt{\sigma}} e^{-\frac{(M-M_{J/\psi})^2}{2\sigma^2}} + N' \cdot \frac{1}{2\pi\sqrt{\sigma}} e^{-\frac{(M-M_{\psi'})^2}{2\sigma^2}}$$

A_N vs. x_F



Theoretical prediction:

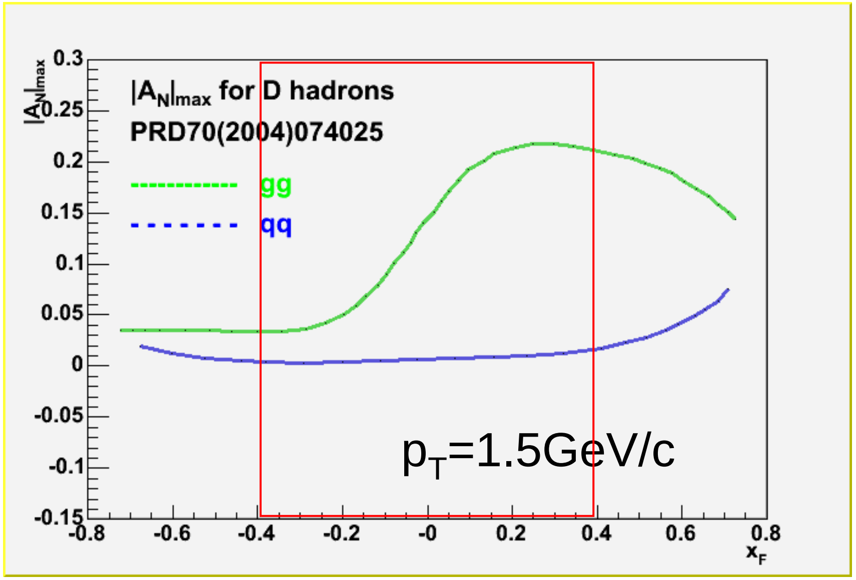
Only available for open charm production

--quark Sivers function set to its maximum
gluon Sivers function set to 0

--gluon Sivers function set to its maximum
quark Sivers function set to 0

*How does J/Ψ production affect prediction?
Waiting for theoretical calculation

* If A_N comes form the initial state→ Disfavor the maximum contribution of gluon Sivers function



Forward neutron Asymmetries

- A_N measurement at IP12 (Y.Fukao et.al., hep-ex/0610030)
  - large A_N was discovered for forward neutrons

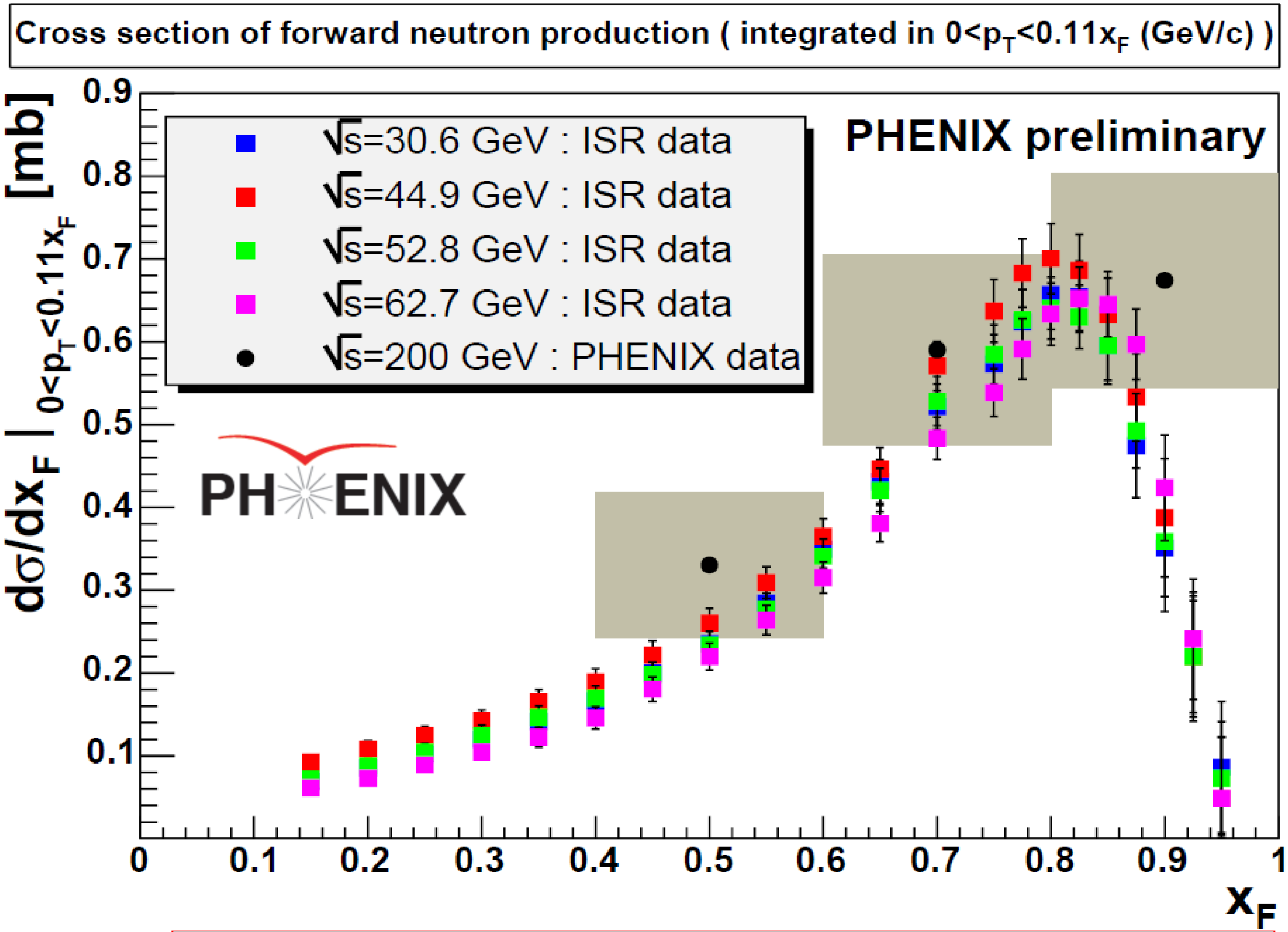
	forward	backward
neutron	$-0.090 \pm 0.006 \pm 0.009$	$0.003 \pm 0.004 \pm 0.003$
photon	$-0.009 \pm 0.015 \pm 0.007$	$-0.019 \pm 0.010 \pm 0.003$
π^0	$-0.022 \pm 0.030 \pm 0.002$	$0.007 \pm 0.021 \pm 0.001$

TABLE I: Asymmetries measured by the EMCal. The errors are statistical and systematic, respectively. There is an additional scale uncertainty, due to the beam polarization uncertainty, of $(1.0^{+0.47}_{-0.24})$.

➔ Local polarimeter at PHENIX

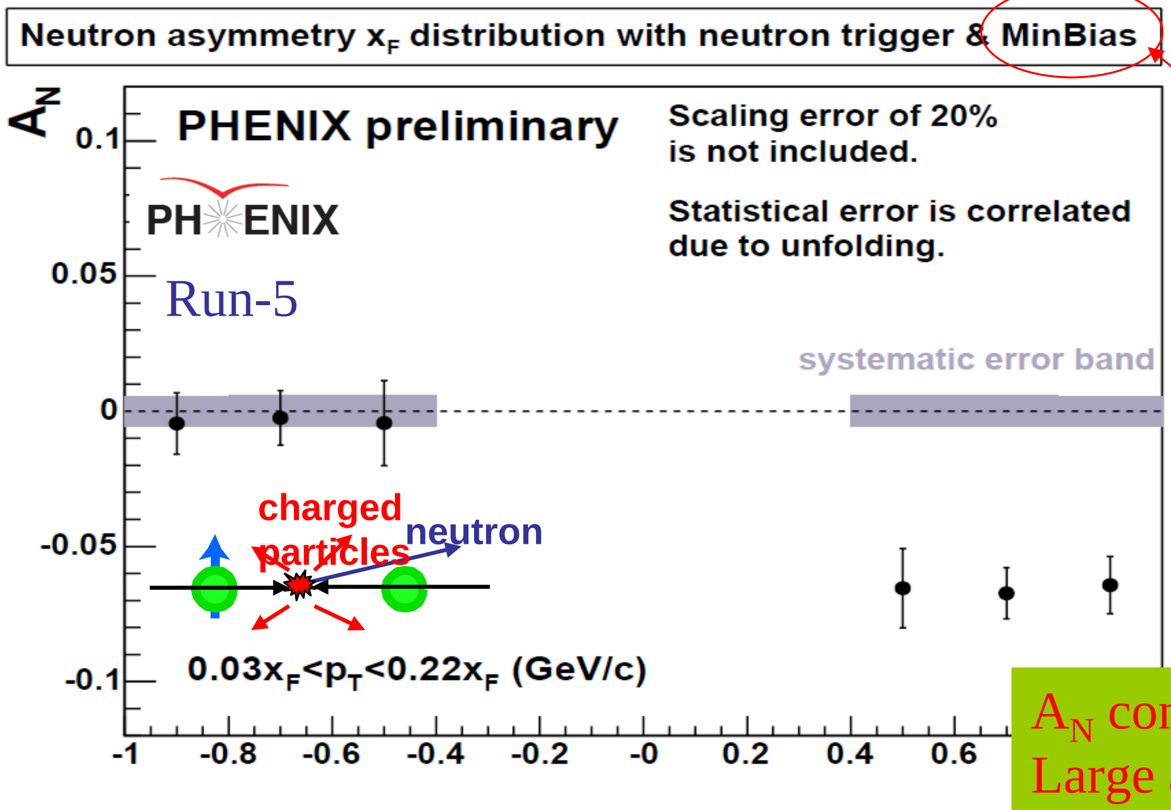
- ZDC + position sensitive counters to measure the neutron A_N
- understand the forward neutron production mechanism

Cross section Measurement



Cross section result is consistent with ISR data

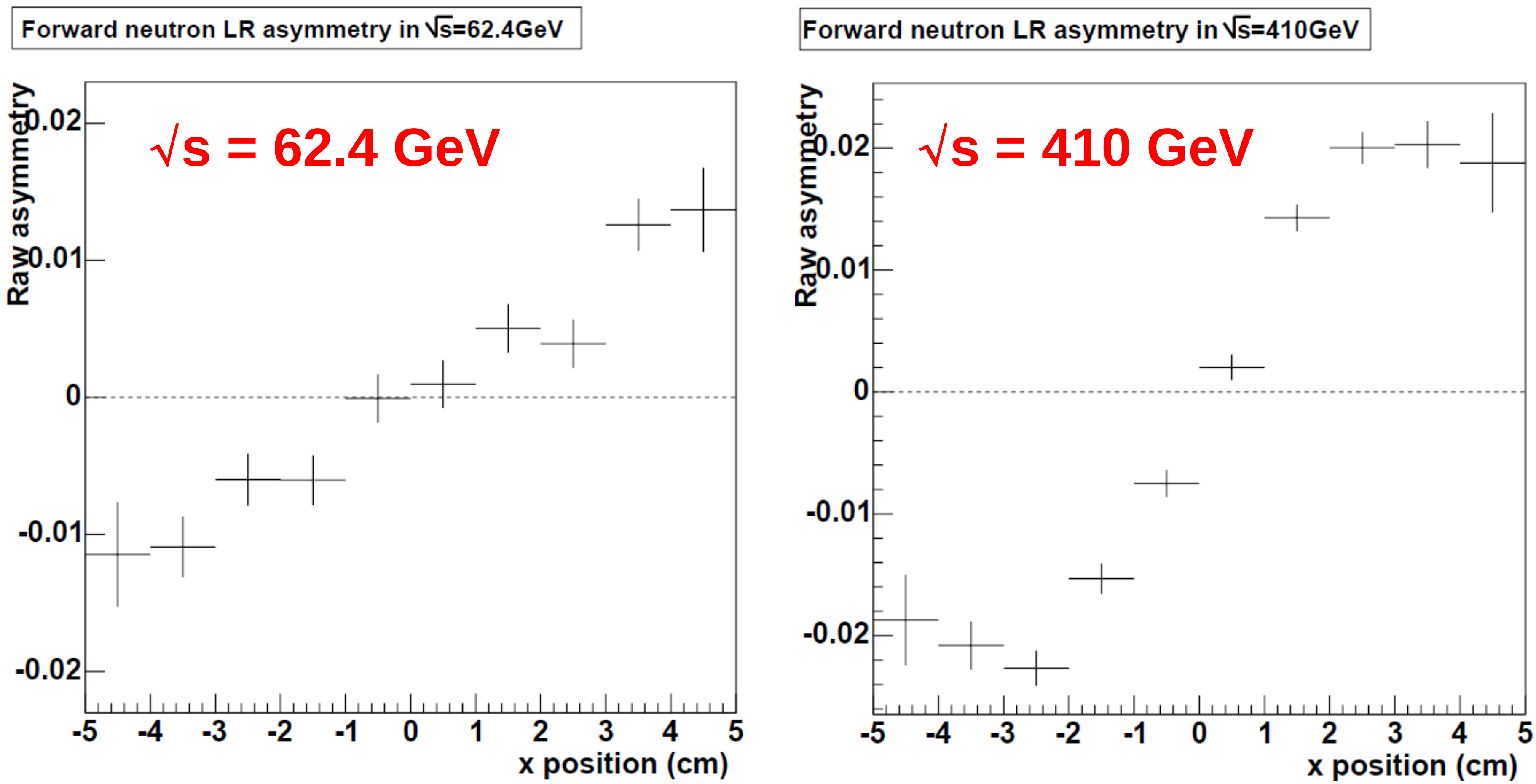
Forward Neutrons at 200GeV



detecting charged particles in BBC (3.0<|η|<3.9)

A_N consistent with zero for $x_F<0$
Large asymmetry for $x_F>0$
No x_F dependence observed

Finite asymmetry persists at 62 and 410GeV



Why such large asymmetries?

- A_N is produced via interference of spin non-flip and spin-flip amplitudes
- In Regge theory

-- A spin non-flip amplitude contribution can be described due to Reggeon and Pomeron exchange

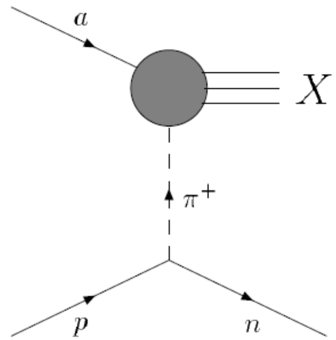
-- We need spin-flip amplitude –> one pion exchange amplitude

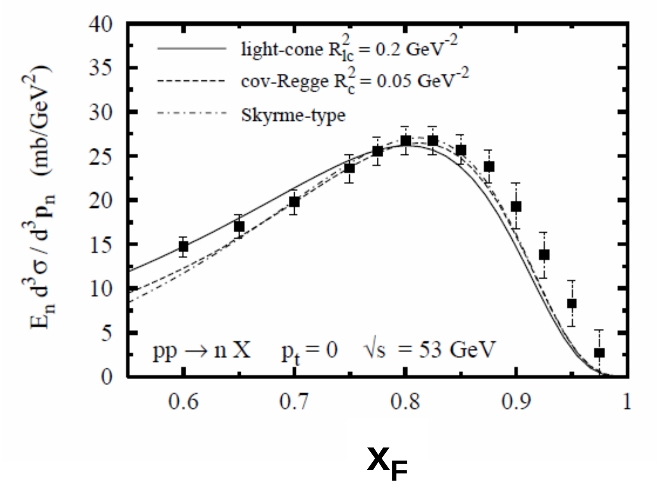
- One pion exchange model (OPE) may explain the result

-- OPE has been used to describe exclusive diffractive neutron production

-- The cross-section at ISR is well described by spin-flip OPE

Eur.Phys.J.A7:109-119,2000





Summary

- Much new data coming from transversely polarized proton interactions
- PHENIX has measured the transverse asymmetry of π^0, $h^{\pm}$, J/Ψ and neutron at two different collision energies (200GeV and 62GeV)

-- In central rapidity, A_N ~ 0 within statistics
may provide information on gluon Sivers effects

-- π^0 A_N at large rapidity consistent with low energy results

-- First measurement in J/Ψ production at $x_F \approx \pm 0.1$
gluon-fusion dominates, possibly sensitive to gluon's sivers effects

-- Large negative asymmetry in neutron production at forward rapidity and backward asymmetry consistent with zero
diffractive-like processes

Outlook

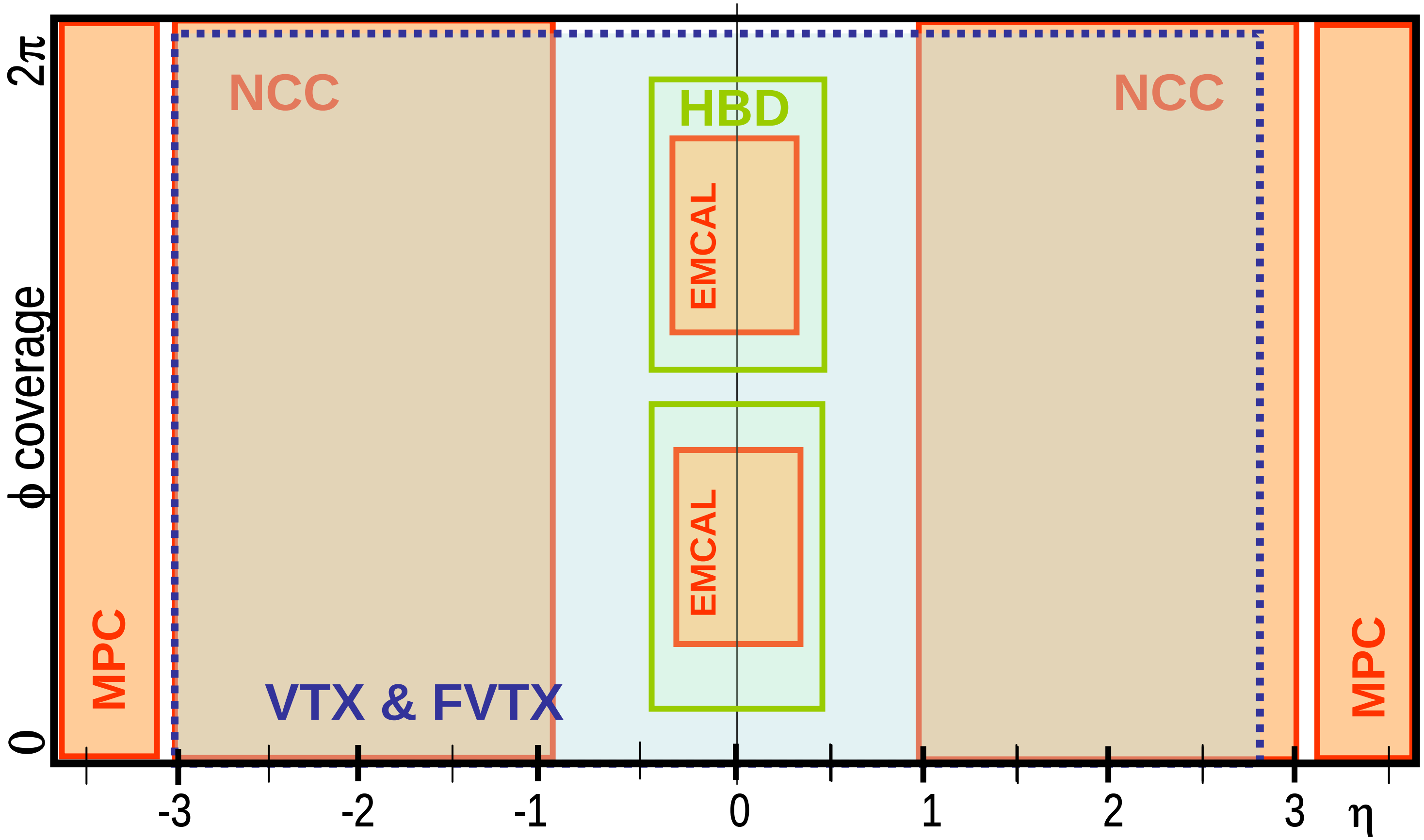
- Central Arms
  -- Two-hadron back-to-back correlations
  (**Boer and Vogelsang, Phys.Rev.D69:094025,2004)**
  Idea: Non-zero Sivers function implies spin-dependence in k_T distributions of partons within proton and would lead to an asymmetry in $\Delta\phi$ of back-to-back jets

- Muon Arms
  -- Single Muons
  Stopped hadrons → π, K
  Prompt muons → Open charm
  -- B2B dimuons → open beauty and open charm

- New upgrade detectors should significantly enhance physics reach
  -- Nose Cone Calorimeter
  -- Silicon Detectors (SVTX and FVTX)

Backup Slides

Future PHENIX Acceptance



- History – PHENIX is a small acceptance, high rate, rare probes (photons, J/Psi, etc.) detector
- Future – Add acceptance and add some new capabilities (hadron blind, displaced vertex)
    - Muon Piston Calorimeter (2006-end): $PbWO_4$ Electromagnetic Calorimeter
    - Hadron Blind Detector (2007-2009): CsI Triple GEM Cerenkov Detector
    - Nose Cone Calorimeter (2010-end): Tungsten-Silicon Electromagnetic Calorimeter with limited Jet Capabilities
    - SVTX (2009-end): Central Arm Silicon Tracker
    - FVTX (2010-end): Muon Arm Silicon Tracker

Comparison with forward neutron

* Asymmetry is 0 when data is selected by BBC only.
* Measure AN of coincident particles at BBC

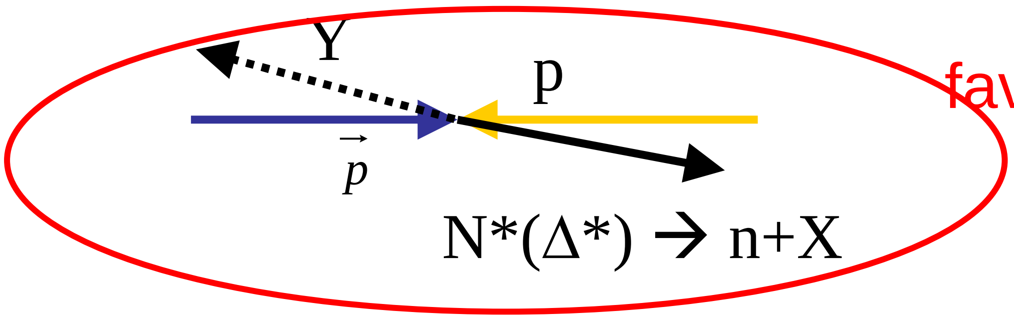
--- Forward neutron, backward BBC (2.28±0.55±0.10)*10-2 >0 4σ

--- Forward neutron, forward BBC (-4.50±0.50±0.22)*10-2 <0 9σ

--- No significant asymmetry for backward ZDC tagged data or in top-bottom asymmetry

* Systematic error doesn't include ANCNI error

- Diffractive-like picture



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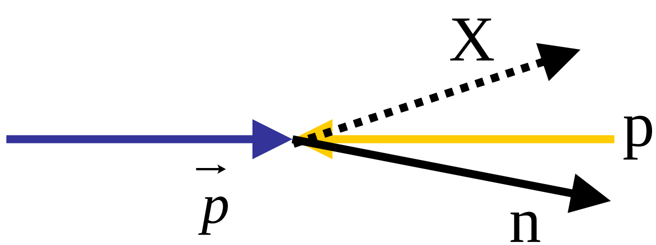
$A_N(X) < 0,\ A_N(Y) > 0$

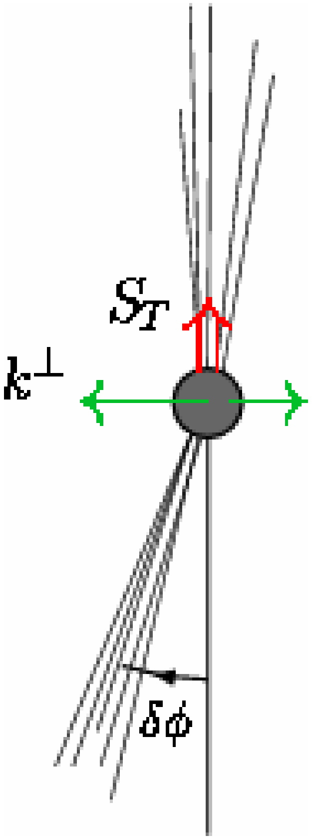
- kick-out/recoil picture



$A_N(X) > 0,\ A_N(Y)??$

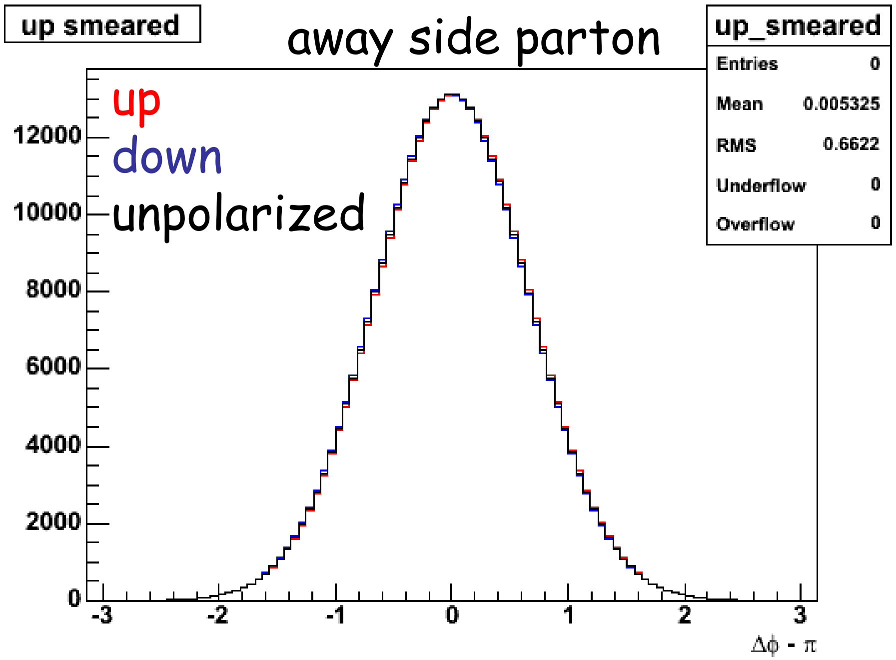
Sivers Fcn from B2B jets Analysis

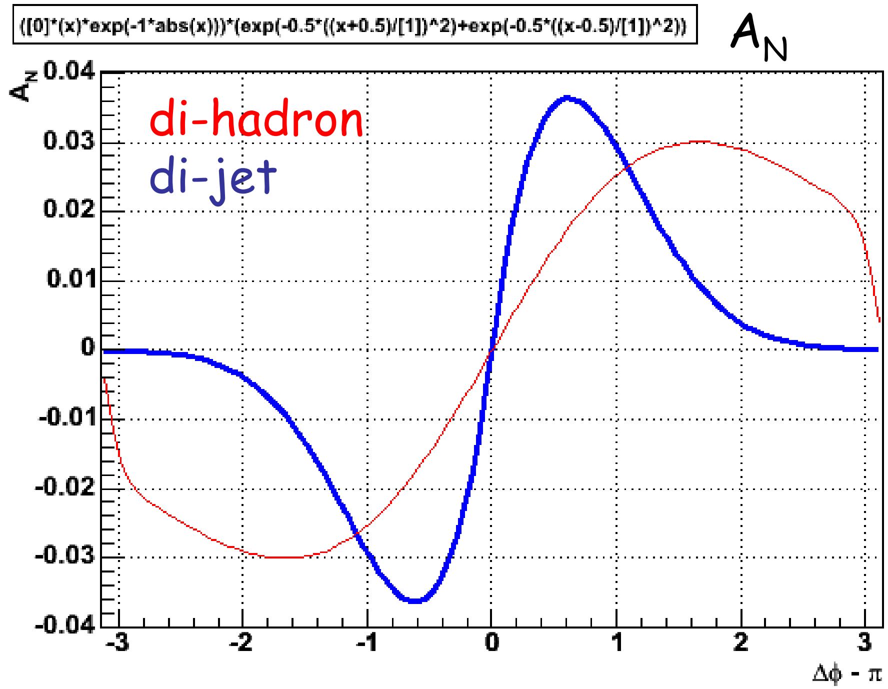
Boer and Vogelsang, Phys.Rev.D69:094025,2004, hep-ph/0312320



- Boer and Vogelsang find that this parton asymmetry will lead to an asymmetry in the $\delta\phi$ distribution of back-to-back jets
    - There should be more jets to the left (as in picture to the left)
- Should also be able to see this effect with fragments of jets, and not just with fully reconstructed jets?
    - Take some jet trigger particle along S_T axis (either aligned or anti-aligned to S_T)
    - Trigger doesn't have to be a leading particle, but does have to be a good jet proxy
    - Then look at $\delta\phi$ distribution of away side particles

A_N Reduction: Di-Hadron vs. Di-Jets





No full jet reconstruction

Use di-hadron correlations to measure jet

Smears out di-hadron A_N relative to di-jet A_N, with smearing function g (assumed here to be Gaussian)

$$A_N^{dihad}(\Delta \ldots = \frac{\iint (N^{\uparrow}_{dijet}(x) + N^{\downarrow}_{dijet}(x)) A_N^{dijet}(x) g(x') \delta(x' - (\Delta\phi - x)) dx dx'}{\ldots)) dx dx'}$$

Broadens and lowers the asymmetry, but still measurable

Muon Candidates

The muon arm is at the forward rapidities of $1.2 < |\eta| < 2.4$

Candidate Tracks:

Prompt Muons

Punch-through hadrons

Stopped hadrons

Decay muons